Zurich, Switzerland
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Brad Nelson

An interview conducted by
Peter Asaro

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Q: Start by telling us where you were born, where you grew up and went to school.

Brad Nelson: Okay, I was born in Southern Illinois, Murphysboro, Illinois, grew up in small towns in Illinois. I went high school in Normal and then to University of Illinois, Champagne, got a mechanical engineering degree. Then I went up to Minnesota to get a master's degree and I went to Minnesota because I heard they had a good controls group and good controls people up there and I wanted to do controls and I got up to the mechanical engineering department and realized all the good controls people are actually in the electrical engineering department and found somebody by the name of Max Donath that was working in robotics, which was about as close as I could get to what I wanted to do, and that was in 1984, and so fall of '84 was when I started reading literature, trying to understand what this field was about and it was a really exciting time in robotics. Some seminal papers had just come out. Things like Hybrid Force Control by Craig and Raibert, Impedance Control from Neville Hogan and these kinds of things were starting to come out, Stiffness Control from Salisbury and I remember Artificial Potentials from Oussama Khatib and it was exciting, and every time I read a paper it was a different way of thinking about problems and then I'd start to see how the people like Matt Mason were looking at manipulation problems and thinking about things completely differently than a mechanical engineer did, and so that was back, I think the mid-'80s was when we thought robotics was – everybody was still a little naive I think about how hard the problems were and while I was in Minneapolis got involved with Honeywell. They were working on a DARPA project called Intelligent Task Automation and there were a couple of different forms of that, one was a big vehicle that was driving it. I think it was out at Denver at an autonomous vehicle.

But ours is a manipulation problem and we worked on assembling Honeywell microswitches for the, I think some kind of a switch that was used in some military component, but it was really just a robotics problem and I remember it had 17 parts to it, 15 of them were different and I can remember each of those parts because I had worked on the vision problem and trying to find them in a tray and locate them and then the idea was to assemble them into a complete switch automatically and we worked with Adept Technology and Jim Maples and some of those guys. We had a force controlled Adept that had force-feedback. Gosh, I want to say it was – we had a JR3. I remember the force sensors. I remember a board that could do 16 megaflops, I think. You know, these things that just seemed like incredible numbers at the time which are nothing now, and we could do, you know, getting to play with just cutting-edge work and then also in that project were people like Stanford Research Institute, Bob Bolles, and the Global Part Recognition System. There were relationships to a lot of these people I had read about and, you know, I think Oussama Khatib was somewhat interested, Tom Binford was somewhat related and I remember feeling kind of isolated at Honeywell because I would come in at, we were doing computer vision on a vac750 and I would come in at 5 o'clock at night when everybody was going home so that I could have the whole machine to myself to do, you know, image processing and things, and then when they came in at 8, I would go home to sleep and then I remember one of Bob's researchers, Jim Herson, came out and Jim worked all night long. I learned how to hack. I learned that it's okay to work these kind of hours, that other people do this to and, you know, I saw this side of how to solve these problems and how to work on them hard and that was exciting, and so did a few things after that, I guess, and then ended up eventually, let's see, left the country for a while, worked overseas and then came back and worked at Motorola in software engineering.

Actually, I was working the telecommunications industry. This is in the early '90s when, or late '80s when cell phones were just starting to take off in the U.S. and digital wireless communication people had this idea you could actually send digital data over wireless and it was a great time to be in that kind of – to be working in that. But I realized I really liked robotics and I heard one of my friends had gone to this robotics PhD program at Carnegie Mellon. They had just started and I was thinking about other schools. I was thinking of Berkeley or MIT, but he convinced me to go there and then I ended up leaving what was a really hot field, data telecommunications and think of this in like 1988, '89, and then going into a field that was actually not too popular at that time, which was robotics. People had kind of woken up to how hard some of these problems were and so went back and ended up in Pittsburgh and spent five years there so.

Q: So that was a whole lot of stuff you did during your master's degree.

Brad Nelson: Yeah. Yeah, so.

Q: So once you started working on these projects, how did you get into contact with so many people, or how did you get involved in the Honeywell project? Was that a grant that your advisor had or were these projects that you were doing as part of your thesis?

Brad Nelson: With Honeywell I was, let's see. I think I was, when I got to Minnesota as a masters I was on a fellowship and then I was looking to do some outside work after that finished and make some money and, you know, somebody put me in contact, I think John Krumm who is at Microsoft Research, he had somehow gotten a position there and said oh, they're hiring students. So I went out and immediately started to abandon my research at the university because of the problems we were working on at Honeywell were really exciting and so that's how I got involved in there and that really opened my eyes to I think, you know, some of the real cutting-edge work that was going on, on the West Coast but also there were connections to the East Coast as well, you know, coming from the mid-West you can get a little isolated sometimes. So that was a good move to go to Honeywell and I spent a couple years there working so.

Q: Oh, okay. So what did you end up writing your master's thesis on?

Brad Nelson: I think the title, I probably have it over here actually, Optimal Location of Assembly Tasks in a Manipulator Workspace, I think. It was – yeah, I remember in '85 a paper came out at ICRA Yoshikawa, the famous manipulability paper that sort of gave a way of analyzing how near singularities, what are some of the problems with the way manipulators were configured and I started looking at – read that paper. My advisor, Max Donath, suggested I look at it because we were working on robotic assembly at the time and I realized I needed to simulate robot motion and all that. So then I, what did I do? I wrote my own robot simulator. I remember that. Yeah, I wrote my own robot simulator, really simple graphics in C, and I used the equations that Lou Paul published in, I think it was called the International Journal of Robotics and Automation at the time, on the Puma 560, which was a manipulator we were using and it turned out those equations were wrong and I was too lazy to sit down with a pencil and paper and re-derive them myself to get them right. So I heard about this computer program that would do algebra, symbolic algebra, called Maxima. So instead of sitting down with pencil and paper to derive the kinematic equations for an inverse for a PUMA, I learned LISP so I could learn Maxima so that I could learn how to derive these equations symbolically on a computer, and then with that it's sort of like you realize oh wow, I can actually calculate determinants of huge matrices automatically. I can take, you know, I can reduce the computation time. Computation was a really big deal back then, to try to reduce that to reduce the calculations. So then I figured out ways I could kind of prune trees to search for optimal locations of these assembly tasks and so that's kinda of how the master's thesis came out. I haven't thought about that for a long time actually.

Q: Did you ever talk to Lou Paul or contact him about –?

Brad Nelson: You know I met him once when I was a student helper at International Symposium on Robotics Research, ISRR. I met him once. I guess I was really intimidated. I didn't have the guts to say how come your equations were wrong, you know. I'm sure I wouldn't have said that. Yeah so, and I remember after I had coded all this and it wasn't working somebody said didn't you know those equations were wrong, yeah, like everybody knew that. I don't know if that's true or not, but. I'm not sure everybody knew.

Q: So who did you work with when you got to Carnegie Mellon?

Brad Nelson: Carnegie Mellon, my advisor, PhD advisor was Pradeep Khosla. He's an electrical engineer. He was a young assistant professor at the time, now he's the dean of engineering there. I started off, again I was working in assembly, looking at assemblability of mechanisms doing CAD-based design for assembly and then I was lucky to get a fellowship from the Army and sort of made me a free agent and so there's another grad student there that had been working on visual servoing for a couple of years and looked like a fun problem, got back to trying to do fast vision, computer vision some, and again, this is back in the early-'90s so a lot different than these days in how quickly you could do computations and that was exciting. I think trying to get, you know, cameras to do fast tracking of objects and then, you know, bring that into the servo loop of the manipulator, and this is again with Puma 560 as we had three of them we used simultaneously we called the Troikabot, and then I thought oh, you know, it would be interesting, I'd worked with force control a bit when I was at Honeywell. So I thought why don't I look at the – how do you do force and vision together and it's still a problem that still interests me. How is it that you decide when to switch sensing modalities and how can you use them in complimentary ways and I still, you know, still think about that, and even though today I'm working in the micro/nano world, those kind of things still are on my mind.

Q: What do you think are the hardest problems in that area of relating force and vision?

Brad Nelson: Hardest problem, well I think in visual servoing I think right away I recognize the hardest problem in visual servoing was the vision problem. Yeah, we could track objects but it was, you know, it was under artificial conditions but the vision problem is the hardest part to solve. You know, in force control it was contact, going from non-contact to contact states, you know, instabilities and things like that were really hard. That was one of the things that was, I thought was kind of cool was I could show how using vision, I could do really high-speed impacts because the manipulator knew if it was getting ready to hit something. I mean it was so simple but it was sort of like yeah, I mean, that's not the way we do it when we know we're getting near something we're changing our parameters a little. So that was kind of interesting I think, but yeah. So the vision problem and also the hard problem was just having a good enough environmental model. We had to have some kind of a model of the environment and how do you create that, where does that come from, how do you parameterize it and then how do you prepare the system for changing from contact and non-contact states and for dealing with these uncertainties.

Q: So what were some of the first attempts you made to do that kind of environmental modeling? What were the strategies –?

Brad Nelson: Oh, I think this is back – boy, this is back in the days of silicon graphics and we had some machines that, you know, big, huge machines that cost a lot of money that do, you know, little solid models and then there was – gosh, I remember like Deneb, was that a company that had a robot simulation model that – so I would represent these just as, you know, as boundary representations in there. So I would try to use commercial packages and kind of break into them and use them and use their engines to do some of the computations so yeah.

Q: So was the Troika the first sort of material robot that you were working with that?

Brad Nelson: No, I worked with Adept Robots in Minnesota. We had one of the first five axis Adepts there. I think well, they used to say the first five axis. I don't know if it was. But we actually had an extra degree of freedom on the end effector. They gave us a fifth degree of freedom. That was on the first Honeywell. We also had a Puma at Honeywell where we did this kind of laser-based visual servoing kind of approach there. But those were the, yeah, the first manipulators I worked with, and then when I worked in Pradeep's lab at CMU we had the Troikabot with three Pumas. We also had the DD Arm, the direct drive arm. This is the second one. The first one was out at Takeo Kanade's lab and Pradeep was a student there and working on that, and then we had the second DD arm and I didn't work on that too much. I did a lot of real-time, you know, we had a home-brewed real-time operating system called Chimera, did a lot of hacking of that and a great way to learn everything about, you know, from voltages and bits and bytes up to Jacobians and manipulator mass matrices and things like that so.

Q: And what was your thesis on?

Brad Nelson: Thesis was called something like Port-Based Agents for Assimilating Disparate Sensory Feedback. It was the idea of trying to identify components of this complicated system that used several different robots with force and vision feedback and represent those as these agents that were port-based and then how do you connect those ports together to get this, you know, more intelligent behavior. I mean a big focus of our lab at the time at Carnegie Mellon was just trying to figure out ways to make robots easier to program, because of course the thing we learned a lot in the '80s was you can build this nice piece of hardware, but programming it was a nightmare and the software and putting it all together was quite – was the challenge and so we were always looking at different ways of getting reconfigurable real-time operating systems, doing iconic-based programming, trying to take components of the system and represent them, and you know, this was back when C++ and object-oriented programming was just starting to be appreciated, what it could do, and so you kind of take some of those lessons from that and bring it together, so yeah.

Q: What did you do after you graduated?

Brad Nelson: So I got about halfway through my PhD, had two kids. Well, my wife and I had two kids during that time and I realized I was working on manipulators and manipulators weren't very popular in the early '90s and all the work had been done and I'm like jeez, what should I do, and towards the end of my thesis I started thinking, you know, what if I took everything I had done with force and vision control and instead of doing it at large scales, what if I did it small scales like under microscopes and I looked at micro positioning and I thought, you know, there could be some interesting applications there and I remember going to Pradeep, my advisor, this is probably my fourth year of my thesis, and I said you know, what if we did this, what if we worked on this? I had played with some microscopes and kind of got an idea of what I thought some of the hard problems were and he wasn't interested. He was more focused on other strategic interests and so I said that's fine. I'm going to just finish this off and then I sent out tons of applications for faculty positions. I think 40-some or something and got almost no response, but I was fortunate to get then an offer from the University of Illinois in Chicago, the mechanical department there as an assistant professor, and so when I left CMU after working on these manipulators, big manipulators, I swore I would never work on anything that wasn't hot, you know, that wasn't because I had my, you know, that's when it became obvious to me.

So I started looking at a few areas and one was medical robotics. I had seen at CMU a great talk by Russ Taylor when he was at IBM doing dog hip implants and things like that with IBM robots and I thought now that looks like a cool area of the future, but that's hard to get into and I looked at that. I looked at continuing with what I was doing just because I knew it, but I wasn't – and you know, you looked at a few different areas but I found an old probe station, an integrated circuit probe station. Basically it's a microscope with some positioners on it and so I got my hands on one of those and started, you know, adding motors and things to it and this was back before I had grad students to do this stuff for me, and you know, had to turn this – basically just an integrated circuit manual probe station into sort of an automated system for trying to implement some of the ideas from my PhD thesis but on a small scale, and that's when I started working in micro assembly, and one of the big motivators for that, I have to say was IROS, one of the two big robotics conferences. IROS was in Pittsburgh in '95, the same, almost, you know, within days of when I finished my PhD and was on my way back to Illinois as a professor and two papers were at IROS that I remember specifically. One was out of Toshia Fukuda's group and Fumi Arai was the first author on that, and the other was from Ron Fearing at Berkeley and I don't remember the exact titles of those. I have them written down. Both of those papers at IROS were on the forces that are involved when you manipulate small objects.

So as things get very, very small, you know, in robotics at that point if you're doing manipulation you thought of two things. You thought of friction and you thought of gravity and inertia. You know, but basically you got forces due to gravity and you've got forces due to friction and then all of the sudden as things get very small because the volumes are so small, the inertial forces, the gravitational forces become negligible, friction becomes meaningless almost in a sense because you're looking at much smaller scale phenomena and you start thinking about things like electrostatic forces, Van der Waals forces, at least more and more chemical kinds of forces that you're used to learning about in chemistry or physics classes and you realize that our sense of how to handle objects is completely different or completely foreign. So that made it an interesting research. There's some interesting researches to be explored and that's what Fumi and Toshi and Ron had identified in these papers and did, you know, a nice job of communicating and that was a good time for me to read those papers. I was thinking about new directions. I had been thinking about going this way and I realized maybe there are some fundamental issues that had some legs, something that was going to last a while. It also happened to be in the mid-'90s was kind of the golden years of MEMS, micro-electro mechanical systems. You know, accelerometers and pressure sensors were out there, airbags were in cars and these companies were starting to make money and people had all these ideas for new MEMS devices, flow controllers, these things to do projections of video using little tiny micro-mirrors that moved and crazy ideas out there.

But there's a huge learning curve to getting into MEMS. You've got to learn microfab, you've got to have the facilities and so I thought okay. The story I made was what if we could, and other people made it at the same time, what if we could instead of micro fabricating MEMS with the normal processes, what if we could actually assemble small things and so started looking at that and found, you know, yeah, there's a lot of issues to explore there. That was back at the time at the National Science Foundation in the US when Howard Moraff was running the robotics program there and Howard was a great supporter of young professors, young people coming in like me and I remember my first career award proposal I submitted. I think like a lot of people you submit a proposal that wants to solve every problem in robotics. You think you're, you know, I've got a lab and I'm going to do that and I think my proposal did that, it did a lot of things. But I called Howard and asked him, you know, about the review, but of course it got rejected, process and tried to get some feedback from him and he picked out one paragraph he said people were really interested in in my proposal on micro assembly. So then I wrote my next proposal just on micro assembly and I think after that got funded, you know, five, six, seven proposals in a row, never got a rejection and then realized hey, this is a good research area. I can sell it, it's got good topics, it's interesting, I'm learning new things and people will give me money so, and about that time then Max Donath, my advisor at Minnesota, called me up and he said I hear things are going well. We've got some openings up here. Would you be interested?

Famous last words, it never hurts to send a CV, and so I went up to Minnesota and after three years at Illinois/Chicago and the great thing about Minnesota was and is, it's got a really good micro fabrication facility, first-rate, good education of students for that and then also good characterization facilities. It has an electromicroscopy facilities and these kinds of things you need, and so I really was able to leverage that. It really took my work, the capabilities we could do. We could actually start to make MEMS devices and things like that. So that was '98, I think I moved up there. It was also the year I met a young kid in China by the name of Yu Sun, who became – I eventually convinced to come to Minnesota and do his PhD with me and he did a lot of interesting work for us in cell manipulation and we worked in manipulating individual biological cells. So we moved from just manipulating and assembling parts to moving into the bio area and other people, you know, started thinking about these lines and you just try to be there and move into these directions and then so in I think 2002 we finally, I got a system to work where we could handle individual cells, we could make measurements and publish I think some of the first work in that area that was really interesting. That also happened to be, and then I happened to – spent about four years at Minnesota, I happened to get an email from a place called ETH.

I wasn't quite sure what it actually was, Swiss Federal Institute of Technology in Zurich and the email said oh, we've got an opening. There's a professor who's retiring and we've got an institute that you could – that needs to be taken over and we think you would be an interesting candidate for that and the job comes with, and they listed, you know, seven staff positions and yearly recurring research, you know, and potentially millions for startup and things like that and you look at that and you start to realize you mean, I don't have to be on a three-year funding cycle anymore, I don't have to think about my next NSF and whether that hits or not and what's going to happen. This will let me think long-term and so famous last words, it never hurts to send a CV, and came out as June, beautiful June. It was June 6th, I remember in probably – I came out a beautiful day, mountains were out and interviewed and you fall in love. It was easy to fall in love with this place on a beautiful day and you see the facilities and the people and Zurich's a beautiful city and so I eventually moved here and so I've been here 9 and a half years or 8 and a half years now, so.

Q: So it was 2000?

Brad Nelson: I actually moved here, yeah, fall 2002, beginning of 2003 so.

Q: Okay, yeah just to go back a little bit, so prior to this, like, year was '95 kind of like some papers that you noted, was it your sense there was much interaction between the MEMS community and the robotics community?

Brad Nelson: No. People were starting to think about it, you know, there was talk. I know back in the '80s or actually when I was at CMU there was a group in Japan, Hirofumi Miura, was working on it trying to make a silicon, I think they called it silicon dragonfly, you know, trying to make something that could fly out of MEMS technology and a very, very difficult problem. At that time though if you went to the MEMS community and you talked about assembly, and I mean I talked – I went to Motorola when I was in Chicago and tried to convince them about this. I remember a quote from one of the Motorola engineers when I was telling him what I was doing and he said well, if you're doing assembly, you're doing something wrong, you know, that's not the way to do this and so it's like yeah, you know, I understand his point. You know, he's not going to – Motorola is not going to build a product that's going to be micro assembled at that point. But there was still that feeling in the MEMS community that, you know, the point is batch fabrication. The point isn't to do this serial thing. You've got to look at that. So other people like Karl Böhringer and I know Ken Goldberg and folks were looking at parallel assembly and ways of moving several objects together. This is kind of the beginning of some of the ideas in self-assembly and out of that community. So there was starting to be interest in assembling these small things, but it wasn't – but the main MEMS community. I mean, they were riding high, you know, they were the king of the hill in research in a lot of ways and huge numbers of conferences and a lot of success and, you know, also in industry in seeing their products or seeing a lot of the technologies develop for them coming to fruition commercially so.

Q: And would you say that the micro asssembly sort of research area now has more of a sub-genre of robotics or MEMS or sort of a hybrid?

Brad Nelson: Well, I kind of classify it now as micro and nanorobotics. I mean they're a somewhat different field but all people tend to work in them at the same, you know, but I think it's a subfield of robotics more than anything but I think we've got more respect in the MEMS community than we used to have, and that's because of people like Fumi Arai and Karl Böhringer who are, you know, first-rate engineers and scientists and they go in there and they're well-regarded and I think, you know, at first, like everything you come in, you don't know what you're doing, you look like an idiot and then you start to understand the issues and you start to speak each other's language and understand why they have their viewpoint and you bring that together, and I think that – so you know, we're not – I think yeah, we're not a part of the MEMS community although all of us working in it are usually, or a lot of us have close connections to it, but we're still – I mean, my home's robotics still. I consider that. These are the main conferences I go to and where my main interests still are so.

Q: So as a subfield, how did it evolve into micro-nanorobotics and do they have a centralized conference?

Brad Nelson: Well, we still kind of hang onto ICRA and IROS. We still have our sessions and workshops there. I mean, that's – I was a part of SPIE for a while, the society of photonics [instrumentation engineers] or whatever, whatever. It's some optical something engineers. We were a part of that for a while, I go to some of the MEMS conferences, I go to nano, you know, I'm editor of the IEEE Transactions on Nanotechnology. But it kind of evolved, you know, I mean I think that the path we took was similar to a lot of folks where you get in, you start to do assembly. I think we started doing more fabrication and things like that then a lot of other groups, but a lot of folks just focus on precision assembly and precision positioning, which is a hard and important problem for industry and that you get in there and then you start thinking smaller, but one person that was ahead of all of us in this was, I think, Ari Requicha at the University of Southern California, and Ari, before you know, while I was thinking micro, Ari is already three orders of magnitude smaller and he's in the nano world and he's talking chemistry and surface effect things, things that at the time I didn't know what the heck he was talking about. But he was seeing the potential of some of his programmable assembly ideas in the macro world and putting them into the nano world and working with a atomic force microscope, scanning probe microscopes and automating those and bringing robotics in, which I think was a – I mean, I looked at it, I thought about it and I thought well that's way too far of a leap for me, but Ari was there working and he did a great job and has done a great job and pulling robotics into that and helping a lot of us see the potential, and he also does the, not just the vision, the research vision, but he also has done a lot of work in helping make sure there's funding there so that the research can continue, he served as editor-in-chief of the Transactions on Nanotechnology and helped bring that journal up to higher standards and so yeah, Ari was yeah, in the nano world I think was really one of the pioneers of that so.

Q: What was the first microrobotics system that you built?

Brad Nelson: The first one would have been when I was in Illinois in Chicago. I found somebody had, in a lab there was a, it was called a Wentworth probe station. It had a microscope, probably a mitutoyo microscope on it and some manual positioners and I remember, you know, thinking about micro assembly, how can I get – I had a whopping $30,000 startup package, this is 1995. $30,000 wasn't very much then even, but I didn't have a lot of money and I was looking at how to get something going and I heard in one of the labs there was this Wentworth probe station and they said it doesn’t belong to anybody, and in 10-minutes I was down there. I think, you know, in a half an hour I had, heavy thing, it did have a table. We had to actually move the whole thing into my lab and I started then getting mechanical drawings on it and we just kind of retrofitted it with motors put on, just D/C servo motors and low-cost controllers and took this manual probe station from moving wafers and probing them under a microscope and then we, I should say I, got the system to work and then my students, people like Barmeshwar Vikramaditya, my students and one of my first real PhD student and then, you know, I worked with him and taught him, okay, here's how you do visual servoing, this is how we track parts and we, you know, and he's a smart guy. He's at Seagate now and he picked all that up and really pushed things and then you train, you know, you get other students.

Yu Zhou was one of my students. He was interested and then I got some money and got an atomic force microscope head and so the days where I, you know, did anything to save a few hundred dollars and I negotiated with the company just to get the key part. I went, I can't believe they sent that to me. Nobody would do that now. They just sent the inner component of the AFM. The whole FM cost a couple hundred thousand and they just sent me the inner component for, like, nothing. I guess I can't believe they did that now that I think back about it, but nobody would do that now. But you know, we started building our own systems from scratch to do micro and nano manipulation and those – but those were all manipulation-based systems.

Q: So what was the assembly problem? What were you trying to actually build with it as a test?

Brad Nelson: Well some of the works were just fundamental. We were trying to do things like come up with good models of microscope, good camera models, optical models of microscopes. If you calibrate back in the days of Tsai, I don't know how people calibrate cameras these days. You don't hear that much about it, but you know, there was the Tsai approach or IBM had developed a camera calibration routine we all used, but the real problem with the Tsai approach was that you had to have 3D information. You couldn't just give it a flat, you know, bunch of dots. They had to have – there had to be a depth to them in order to get this algorithm to conserve to, the word is escaping me, to converge. I said conserve, okay, to get the algorithm to converge and so that algorithm wouldn't work. So then how can we calibrate a microscope, you know, that way and then we got to come up with a new models, so it was a fundamental problem. Another one was, you know, we wanted to do high precision positioning and a lot of people had looked at subpixel sampling. So we looked at okay, how much can I get, you know, can I get below a wavelength of light? How far down can you go? Then with the AFM we started going and looking at the mechanics of manipulation and in other words, what are some of the surface forces involved and how can we quantify those and how can we model them, things like van der Waals or when it is electrostatics, surface tension if you got it.

So a lot of it was very fundamental work and then I would get some industry projects, like I worked with Seagate when I was in Minnesota and they had a little motor, a tiny little motor they wanted to put on the end of the head of a read/write head to nanoposition the read/write head. Well it turned out that motor, the design they gave us needed assembly and needed had these little, tiny magnets that were a couple hundred microns, about a fifth of a millimeter on a edge and about a half a millimeter long, and four of those had to be picked up and assembled. You know, that was a system. I had a telecommunications company that came to me and wanted arrays of microswitches, can we design microactuators and so we looked at a lot of different designs. Some of them required micro assembly, some of them didn't and then so we were kind of driven research-wise, NSF-wise was more fundamental work and then industry-wise we try to find interesting projects to see did it apply, that seemed like a good strategy at the time so, you know.

Q: So was there anything that you, when it was assembled you'd call that the microrobot. I mean is this a component of –?

Brad Nelson: Yeah, so we used to use the term microrobotic system but when I got to ETH, remember this is in 2000, late 2002. All of the sudden I had many more resources available to me than I had before and, which is why I came here. But when you actually have those resources and you think, “What'm I going to do? What can I really do to make an impact?” you start to try to think long term. You start to try to think of the things that you thought were interesting. And so I go back to Russ Taylor, for instance, and the robotic-surgery talk that I saw back in the early ’90s. I was thinking of that. That’s a field that’s going to go somewhere. So, back at 2002 there’s two products that had just come in the market and passed clinical trials, I think, and that were being commercialized or in clinical trials. And one was Intuitive Surgical’s, Da Vinci robot, robots doing surgery while the surgeon’s across the room tele-operating them. And the other was the Given Imaging camera pill. They swallow the pill and it goes through your body and takes 50,000 images over about eight hours and saves them to a disk you’re wearing. And those are exciting. I mean, these technologies are out there, and, again it was like the MEMS – in the mid-'90s you could see these fields rising, and it's a really bad time to get into a field when it's rising that way when you realize people have been in this. You think, "I don't want to just jump into this right now. I want to try to figure out where it's going to go. I want to try to predict where things are going to be heading." And so we started thinking about where might some of these fields be heading, and it seemed natural. Eventually with Intuitive Surgical you want to get rid of the robots off to the side. You want to just swallow the robot like you swallow the camera pill. You want to think, "If I can make these things smaller, what might they do?"

And the other thing I realized – this is – one of my post-docs at the time, guy who worked for me for eight years, Karl Vollmers, he was one of the first people to come here with me. And I had an ETH apartment up the hill here, and he was staying with me for a couple months until he found a place, a little one-bedroom place, and we would sit around and talk about what our idea – and we both realized people are much more interested in the things we were building than in the processes we were using to build them. We were making these micro-robotic systems to pick things up and assemble, but people always got much more interested in what it was we were assembling. And the other thing Karl and another one of my Ph.D. students, Shan Guan, worked on – we'd worked on different magnetic materials for making micro-switches and things like that, and so we had expertise in how to assemble small things. We had expertise in magnetic materials and small things. I was thinking medical robotics is the future in a lot of ways, but I don't want to just do an Intuitive clone. I want to do something different. Why don't we see if we can make really small things and cut the tethers? And that's when we first started making true micro-robots, things that didn't have tethers that were moving without wires. And that was 2003 we started developing these ideas. Berk Yesin moved out here, had about six or seven – when I came from Minnesota to Zurich, I think about seven or eight people came with me, counting family, my family. I counted 17 people moved from Minnesota to here when I came, and so we started thinking, "Where're we going to go with that?" Berk Yesin came out.

We started thinking magnetic fields just make a lot of sense, because you can project them over certain distance. Doctors are comfortable putting people in magnetic fields, and we didn't know anything about magnetics hardly except materials. I mean, we knew a little. So Berk built a planar system that took a little millimeter-sized nickel micro-robot that we micro-assembled and used external magnetic coils to drive it through this maze and move it through. And we were like, "Maybe we can do something." We do the math and it's like, you're not going to get one of these things to swim through the heart, but if you can get near it, you might be able to get – just generate some motion. So you do the physics, model. And so we started getting this vision of small micro-robots in the body, and we thought we were the only person with a vision, and then we found out that Sylvain Martel also was working at – he was at Ecole Polytechnique [Montreal] at the time and he had this idea of using MRIs to guide little particles, and it was good for us to find that out. It lit a fire under us to move quicker. And so, we started going along. I started thinking of how we might use these. I went back. Russ Taylor comes up. Greg Hager is at – Hopkins was working with Russ. They were thinking about eye surgery.

I also talked to Cam Riviere, at CMU, who was working on a tool for doing eye surgery, and they were telling me about how the forces weren't known. Cam was saying we should use some of these manipulation devices we made, some of the force sensors we used to try to measure some of these and quantify them. So we started looking at eye surgery and we go, "Maybe this is a good place to start." So, for several years we've been looking at how we can make things that can move through the eye. We call it a micro-robot. It's a hunk of metal with some functionalization on it, and then the whole robotics is really the field, the way we generate the fields on the outside, but the math for that is pure redundancy control of manipulators, stuff. It's stuff that's 25, going on 30 years old now, a lot of the fundamental work, but it's done in a different way. But that's when we started thinking, and that's when we started making micro-robots, and now we just keep going in that direction.

Q: So, the one that went through the magnetic maze was kind of the first one. What are some of the other systems that you built?

Brad Nelson: So, we did that and we were understanding our models. We were really just doing physics and trying to understand things, and then Allison Okamura at Hopkins – I was visiting there once, and she says, "I've got this really great student. I think he would really be great in your lab, Jake Abbott." And so, Jake came out and he spent three years in my group, and my instructions to him when he got here was, "You see what Berk did with the planar robot moving through the maze? We want to do that in 3D." Going 2D to 3D's often trivial, right? So, seldom trivial, really, right? And then Jake, he started – basically had his own little team here and started thinking how we might do that and came up with, I think, some really interesting technology. We got a patent on it and – actually, we've licensed it now to a startup company that's trying to – using this technology to build biomedical devices. And…

Q: What's the company?

Brad Nelson: The company's ANT Scientific. It's an ETH spinoff, and it's – three of my former students are the core people on it. One's the CEO. One's the CTO and the other's the guy who's basically product development. He's trying to figure out applications for this, and so…

Q: When did they start out?

Brad Nelson: Last fall.

Q: Very nice.

Brad Nelson: So they're very new, but the idea now is you get along in your career and you get to be my age, you start thinking, "Do I need to publish another paper? I mean, I really don't need another paper but I do want to see the technology in the real world at some point." And that's what you've got to do, either license it to somebody and let them take it or see if you can – this is a bit of a leap to use some of this stuff, so we're going to try to do it on our own and partnering with other people there, so…

Q: Have there been other startups that come out of the work –?

Brad Nelson: Yeah. So, there's another one called FemtoTools, and they're successful. They sell product. They've got five employees right now. They're growing, and they basically – this goes back to manipulation. This is where we got our start back in the early '90s, early 2000. This is back to Yu Sun. He got one of our force-sensing device that could make measurements at scales that you couldn't get anything for cell handling to work. And then Felix Beyeler, a Swiss student, came and took his design and really extended it, I mean, kind of hardened it, did new things with it. And then Felix was interested in seeing if he could – we knew there's a market for it, because every time I'd give a talk, people would always come up and say, "Can I get one of these? I really need something like this." And so, back, I think, in 2007, 2008, Felix spun off this company and a few of my other people went with him and spun that off, and that's – as I said, that sells product and growing company. And they sell micro-manipulation systems and tools, grippers and force sensors and parts for that. So, it's satisfying to see your research get to a point where somebody's willing to pay money for it in the real world, not just research.

Q: What about your other collaborations with various corporations? I mean, obviously you worked at Honeywell, but other places where your work has been used by industry.

Brad Nelson: Well, we did a lot of work with Seagate when we were in Minneapolis, and then we developed some devices for the telecommunications company, which they've patented. And this was just before the telecom crash in 2000. So then plans change when industries crash. I mean, we've got other companies we're working with right now, but I think there's two ways to make an impact with your research. One is to get companies to use your technology and get it out there, but the other thing that – you realize it's probably the more important one is to bring in really good students, show them some interesting area, and then they're the ones that go out there and they start leaving the company. And a guy like Vikram at Seagate – I know some of my folks have gotten different companies. They rise in the company, and Berk's at AVB – was at AVB and led product-development teams and now has moved into new areas, different areas. And so you realize it's the students, the good ones, they're the ones that are really carrying the torch when they get out there into industry and start implementing these new technologies, I think.

Q: And who are some of your other students? Have any of them wound up in academia, as well as –?

Brad Nelson: Yeah. Several. So Yu Sun is at Toronto. Jake is at the University of Utah. Ge Yang is at Carnegie Mellon. A good nanofabrication guy, Arun, who did some beautiful work in carbon nanotube devices for me, he's just moved from Sandia and now he's moving to Virginia Commonwealth University. I should mention Li Shin. Li Shin joined my group, I can't remember, 2003 or so. I was actually advertising for somebody in the area of biology for a post-doc, and Li Shin came to me at a conference. I knew Li Shin from his work in Fukuda's group in Japan. In his Ph.D. thesis he'd done beautiful nano-manipulation work. And he said, "I'd be interested in not maybe doing biology but working in this other area." And Arun, who was a former student of mine at Minnesota, a master's student then, also told me he'd like to come back to Switzerland as a Ph.D. and he was interested in similar topic. And then I also had a really good German student, Dominik Bell, who's now CEO of Aeon Scientific, and he joined us. All of a sudden I had this nano group of really first-rate people. Li Shin and Arun and Dominik and then some others joined, and so that's where we – really how we did the nano work, got involved in there. Li Shin is at Michigan State. That's how that started. So, Li Shin is a professor there. Boy, I should have a list. I'm forgetting people, I'm sure, but it'll come back to me at some point.

Q: How many Ph.D.s do you think you've supervised?

Brad Nelson: God, I don't know. I haven't even counted. I don't even know how many people work for me half the time. Let's see. I don't know if I've had 20, 25. I guess I could count the number of theses I have on my bookshelf, but I know some of them don't give me their final copies, so it's probably not right.

Q: So, apart from students, have there been some other really important collaborators that you've worked with over the years that've been influential on your work and development?

Brad Nelson: Gosh, yeah. Let's see. I mean, as a Ph.D. student I was two years – I think I'm actually older than Nikolaos Papanikolopoulos, but he was ahead of me as a grad student and he was sort of my big brother and he showed me – well, he's Greek. He didn't show me how to write good code, that's for sure, but he showed me how to do math right, and we did a lot of just LQR, LQG stuff. That was good. I mean, of course, Pradeep and Max Donath and all these people are good. And at Illinois - Chicago I had professors that treat you well and mentor you and people like Sabri Cetinkunt going in to Minnesota, who – or I mean at University of Illinois at Chicago and – so that's been important, and then, I mean, people that're pretty open with a lot of their work and help us, guide us into areas. The Hopkins people have been good. Russ Taylor and Greg Hager, I mentioned them. And then, I mean, the micro-nano community, I think. We all sort of look at each other and try to take the next step and look at different things. So, in Europe there's a lot of good micro-robotics folks. There's the group in Besançon, Nicolas Chaillet, and Michaël Gauthier, some of those folks there. Up in Germany there's Sergej Fatikow and his micro or nano-manipulation group up there and, of course, Paolo Dario at Pisa. When I first got here, he helped me get into the E.U. cycle and become a part of the European Union funding cycle. So, I think I'm forgetting lots and lots of people. You don't get there…

Q: <inaudible>

Brad Nelson: And then we work with a lot of folks in different fields and just being able to interact a little with, for instance, biophysicists, I mean, a guy like Howard Berg at Harvard, who did a lot of bacteria work. I spent some time with him, and just listening to a guy like that, who was at the beginning of understanding bacterial motors. A 20-minute talk from him, you learn more in 20 minutes than you learn a week at a workshop. I mean, initially in robotics, I mean, I was inspired by, I mean, to me, people like – I mean, there's a great paper, Erdmann – there's a fine motion-planning paper, Mike Erdmann, and, I think, Matt Mason and Russ Taylor, I think, were on that. These kinds of things, these kinds of people and seeing this work that just blows you away. And when you're just a mechanical engineer and you see these different ways of approaching problems when you're young is really intimidating. I remember when I was at Carnegie Mellon, the first two Ph.D. theses I saw were Ken Goldberg's thesis and Shree Nayar. Ken's at Berkeley. Shree Nayar's at Columbia. I remember my first semester going to those and just thinking, "My God, this is what they expect me to do? This is unbelievable," to see the quality of work and these guys are so well-spoken. That's why you go to these places and it really raises your level, right, when you see people like that, and it makes you want to try to strive for something like that, a guy like Takeo Kanade at CMU running the Vision Autonomous Systems Center. He's my academic grandfather. And seeing the work ethic but the creativity that he has, and these are the kinds of things that impress you.

Q: So, when you arrived at Illinois – and I could ask the same question about Minnesota. So how were you received as sort of a roboticist within – what is it, the mechanical engineering department?

Brad Nelson: Yeah.

Q: Were there other people working in that area, or were you – were they trying to get into robotics?

Brad Nelson: So I arrived at Illinois-Chicago in '95, assistant professor. In a lot of ways, robotics was a bad word back then, and I think for good reason. First of all, the field had overpromised in the ’80s what it could deliver. I also think there were a lot of researchers, academics, who didn’t know what to do. They didn’t have a good view of where’s controls going? Where was manufacturing? And so they said they were doing robotics and they build little things and there wasn’t a lot of – there just was not a lot of depth into thinking about what they were doing. And you look at these schlocky little things and if you’re a thermodynamicist working with statistical mechanical – doing some pretty detailed theory, and you look at this stuff and you kind of raise your eyebrows and like, “Who are these jokers?” And it can create bad reputation for the field. So you come in there. I remember during my interview at Illinois-Chicago I went into – Selçuk Güçeri was the department head at the time, and I went in to his office to talk to him, and this is one of my first real interviews as an academic and probably my only real interview at that time, actually. And he’s looking at my CV. He says, “Ph.D. in robotics? So is this a real degree?” I just about had a heart attack. I’m like, “Yeah, it’s a real degree.” And I still feel there are people out there who still see it that way. I think in this department here there’re still people that think, “You guys are just building junk. There’s nothing to it. You’re just building stuff. There’s no depth to it.” And the same people haven’t ever tried to build something, so they don’t really understand the difficulties, I think, usually. But that’s one of the reasons you do it is because it’s so wide open, I think, so there’s so much to do.

Q: And in terms of funding over your career, where have you sought funding and where have you received funding for your work?

Brad Nelson: Well, in the States, I mean, the National Science Foundation was very good to me. ONR[Office of Naval Research] - I got the Young Investigator Award. I was on a couple DARPA grants and I had industry money coming. I had some good industry money. I never had a problem in the States with funds other than my first year, like everybody, but then I left before – I came here before a lot of the – well, I came here in 2002, and, let’s see, when was – there was a new president around that time, I think, and things kind of changed then. I think priorities of the country changed. And so, now, here, I have basic funding, so I have a group and I can keep people around for years. I can keep memory in the system. I keep chemists in the group. I keep a guy who’s an electrical engineer who’s been here 30 years and he designs electronic boards for me and it’s a key part of our success is being able to exactly get the kind of electronics we need without having to fit a round peg in a square hole. Then I have my systems engineers. I have my fundamental robotics people, but I’m able to keep that here, so I’ve got that basic funding. But then here in Europe and in Switzerland, I mean, there’s also the Swiss National Science Foundation. I’m a research counselor for that, so I also help determine how that money gets distributed a little. I have some say in it, not a lot. European Union funds, things. Switzerland has a program that helps – that’s more near-term product, so it’s a federally funded government program that you don’t want to do basic research on it but it kind of helps develop a product. And so, with some of the startups, we’re able to leverage that money.

Q: How does that work with Switzerland not being part of the E.U. but still being able to get E.U. funding?

Brad Nelson: So, it's changed since I've been here. I mean, it used to be if you got funded on an E.U. proposal, then Switzerland had an agreement that they would just put the money into the E.U. proposal and it would come back to you. But since that time, it's changed and now Switzerland actually makes a contribution to the E.U., and then just based on the valuation of the proposals, some of that money comes back. So it's not one to one like it was. So, as I say, that's the way Switzerland behaves here. They are good at – boy, this is – let's see. They participate in the E.U. when it works out for well for them, I should say, but they become a part of the community, and I think that's the real benefit I've seen of being a part of the European Union funding cycle isn't necessarily – I mean, you do interesting projects, but really it gives me a great chance to meet and work with people all over Europe, I mean, people like Paolo Dario in Italy or Sergej up in Germany or the folks in France, Antoine Ferreira, the folks in Besançon, people all over, Bulgarians, Finns. So, I think that's the one thing that this has done is it's really helped at least my perspective. It seems to bring the science in Europe closer together, so that's done that. We get some industry funds here. I'm not as hungry for that as I was in the U.S. In the U.S. I would basically help develop products and give patents if I could just to get money, but here it's like we can be pickier and choosier here. We can choose our problems a little more, our interests and what we think is best. So it's a bit of a different system here.

Q: So, what do you see as kind of the future of micro-robot, nano-robotics? What are the big, sort of outstanding problems and research directions?

Brad Nelson: Well, I think in the immediate term what I'm looking at are, first of all, applications. How're we going to use these? What can they really do? I think there's really interesting evidence that targeted delivery in various parts of the body can have dramatic impacts on recovery from diseases. We see that in the brain, and we're seeing that in the eye now, in the retina, and I'm sure as we start to rethink the way we might get drugs there, I think that it's going to be really interesting to figure out, "Okay, how do we get things on these robots? How do we get them there?" That's one of the things we're working on. How do you make these things move? One of the big open issues is the imaging problem. How are you going to see these things and find them in the body? Can you instantiate behaviors on them in some way so they can behave much like a bacteria does, where they're basically following some kind of a gradient, some chemical gradient or light gradient or pH or something like that. I think that's where I'm looking, and if I were starting my career over again building a lab and thinking about interesting problems, I would love to work on figuring out all these little molecular mechanisms that're – I mean, they're little tiny machines.

They're little O-rings that – two kinds of proteins that just naturally form these beautiful O-rings, for instance. On an E. coli membrane there are sensors. There are communication pathways that're very chemical but mechanical, in a sense. I think understanding these, I think, robotics has a lot to bring, because there's a lot of modeling. There's a lot of kinematics involved. There's a lot of different forces and many, many degrees of freedom, so I think the motion-planning community – I mean, these people are working in these areas. I think there's really exciting areas out there to go at these scales. Simultaneously while we're doing that, I mean, I'm an engineer. I want to build something useful. I mean, I'm happy to explore things and that's exciting. That's what gets me up in the morning, but I also want to make sure what I'm doing has an impact, and so I think on the other side we now think and understand – work closer with the doctors, the biomedical people who understand the issues, the problems, and then think, "What are the tools that we can bring to bear on these problems?" And so finding the applications and then functionalizing, I think, are interesting. And, like I said, imaging is a key problem that I have not had the guts to jump into enough yet as much as I need to. That's one of the reasons to work on the eye, because we can just look through a microscope and see it instead of worrying about that.

Q: A lot of the biorobotics work that's been done is sort of interfacing neurons with robotic systems, electronic systems, but there hasn't been as much of the sort of mechanical interaction between the biological side and the robotic side, or would you say that –?

Brad Nelson: Well, I mean, we've worked with biologists. We've studied drosophila, how fruit flies fly, and when you do that, basically we build the tools for the neurobiologist to make measurements. It's the lift force of the fruit fly. What's its bandwidth or something like that? But as you work with them and you work with things like C. elegans or you work with zebra fish or E. coli, you can't help but get ideas on how to build new kinds of micro-robotic mechanisms or use some of these physical principles that – why does E. coli have a rotary motor? Why does it have this corkscrew flagella on it? Well, it turns out from a fluid-dynamics perspective it's a beautiful design. I never would've dreamed of it. But then it turns out Geoffrey Taylor did it back in 1952. I wouldn't have thought of it, though. Anyway, I'm rambling about the previous work in this area, but I think that there's interesting work in Germany in the '30s out of this thing. But why are these organisms – how did they evolve to use these in this way in this little niche, these little physical niche, these mechanisms that I as a mechanical-engineering designer wouldn't sit down and come up with on my own. So you look at those. But I think as we go smaller and we start to look at these molecular mechanisms, all of a sudden you realize we have to look at nature. I just really think that the problem is too – there is a computational issue. There's a search issue that we're never going to overcome, where we're going to be able to design mechanisms that are half as capable as these proteins that come together to form these structures. I mean, there's the DNA origami people, people that're looking at using DNA, the semen work that started 20 years ago, and there's an interesting community there. But that's just the tip of the iceberg of what's going on at these scales, and there's all these things if we just look at nature and look at if we get good cryo-transmission electron microscope images and better ones, then we can start to really visualize these mechanisms and things. I think, boy, that's fascinating to me, and I think that would be a great area to head in.

Q: How far off do you think it is before we can assemble biological systems of our own design?

Brad Nelson: Well, I mean, if you talk to geneticists, I mean, there are things they can do now. I mean, I don't know. When I talked to them I was mentioning this O-ring. You take Fly N and Fly M, and there are a couple of proteins. And they just come together and fit in a certain way and they form a ring. As an engineer, I'm curious what are the process parameters. How robust is that? When will that not happen? What concentrations do I need? What temperatures will that happen? Is that a tool I can build something else off of? But I can build that, I think, now. Kelly Hughes at Utah tells me he can build flagella. He can just build a flagella, get a whole bunch of them. Then, I mean, you look at the synthetic biology people, I mean, they think they can do all these things. I think it's a great field. Like everything that's new, I think everybody underestimates the complexity of it, just like we did robotics in the '80s. Probably we're still underestimating its complexity, but I think the complexity of these problems is really difficult to get a handle on when you start. We learned that for decades, many, many times in many fields.

Q: And what's your advice for young people who'd be interested in pursuing a career in robotics or micro-robotics? What should they do and how should they go about it?

Brad Nelson: Well, I think if you want to work in robotics, I mean, the first thing is you got to have a passion. You got to be willing to come in to work at five in the evening and go home at eight in the morning, if that's what it takes. But you also have to make sure you're working with the best people you can work with, because my experience is everybody else is smarter than you are, and you better go out and grab their knowledge and try to learn the lessons from them, right. And what is it? Anyway, you just need to work with the best people, and then you build these networks and, I mean, it's a fun community to be a part of, because especially if you've been in it as long as I have now, over 26 years or so, you see the field. You see areas grow and wane and then you see things come back. You know the groups that you can trust and you think their work is – if they can't solve it, you know you're not going to be able to, or if you think it's interesting, there might be something really there. But I think working with – just that interaction with the top people in the field brings you up, I think. I mean, there's advice if you really want to make an impact in the field, go to the scales. Go to the one end, the very, very far end, or we went to the very small end, but you can't go much smaller than we're going now. We could talk quantum robotics and I know T.J. Tarn talks that, but I have an idea of what it might be, but I'm not willing to say it, but it has nothing to do with small. It has something to do with the philosophy of the field.

But I don't know if there's extremes of the field to go in right now, but I think there's – I mean, medical robotics is exciting. I mean, when I first saw Russ Taylor give the talk in 1990, I think it was, or '91, I could tell it was going to be exciting, and I think it's more exciting than ever. I think there's a ton to do at molecular levels. We're just starting to scratch the surface, and I think we'll do interesting things. But then you see military applications and you see that is pushing the technology in incredible ways. People talk about service robotics, and I still think that's a completely open issue. I don't understand. I'm not sure how these things are going to be accepted. Everybody's got their own view. I mean, the Japanese have their view of it. Americans are going to have their view and the Europeans are working in these areas, too. But I think there's a lot of interesting areas, but as long as you go into one that – and work with the best people and you're passionate about what you do, good things happen eventually.

Q: Great. Is there anything else you'd like to add, all those things we missed?

Brad Nelson: Gosh. I don't know. No. I just look back. I guess talking about this, it's interesting. I mean, in '84, falling into robotics accidentally, it's amazing how it's a passion. Anything that has anything to do with robotics I still read, even though I work in micro-nano. It's a fascinating field, and it'd still be interesting to see where it's going to go, because I'm not willing to make a prediction, but it's clearly here for a long time, forever, as far as I can see, as long as we're here and somebody's going to be trying to make smarter and smarter machines, things that're more intelligent. And so, I was lucky to sort of accidentally fall into it and happy. I'm happy to be a part of it for such a long time.

Q: Were you influenced by any sort of robotic sort of literature or movies as a kid?

Brad Nelson: My mom has a picture of me in third grade. For Halloween I was a robot. No. I think as a kid I was influenced by the Apollo missions. I was seven years old when they landed on the moon, and I didn't want to be an astronaut but I wanted to know how to build a rocket. I wanted to know how to build the Eagle and the modules and the lunar modules and what those were. And I think more than anything that got me excited about engineering was the space program in the '60s and '70s and landing on the moon in July. Is it July 20, 1969, I guess, right? Was it?

Q: July. Something July.

Brad Nelson: I think it's July 20, 1969, and 7 years old. That's a good thing for a – that was back before all these toys and everything. You had to really want to follow these things if you were interested in it.

Q: Good.

Brad Nelson: Thank you.